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Wood anatomy and properties of 24-year-old *Liquidambar styraciflua* in three diameter classes

Anatomia e propriedades da madeira de *Liquidambar styraciflua* aos 24 anos de idade em três classes de diâmetro

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Resumo

Investigamos o efeito da classe de diâmetro sobre a anatomia e propriedades da madeira de *Liquidambar styraciflua* com 24 anos de idade para determinar a qualidade potencial da madeira em três classes de diâmetro: grande (33 cm), média (26,5 cm) e pequena (22,4 cm). Hipotetizamos que diferentes classes de diâmetro têm variações na madeira que refletem em diferenças na qualidade. Maiores valores de resistência a compressão e cisalhamento paralelo às fibras e módulo de ruptura ocorreram nas classes pequena e média. Radialmente (medula-casca) ocorreu um aumento no diâmetro e diminuição na frequência dos vasos e aumento do comprimento da fibra. Fibras mais longas foram encontradas quando comparadas com outros estudos, possivelmente devido às condições climáticas. A densidade não variou entre as três classes, mas foi mais homogênea nas classes grande e média. A rigidez foi mais homogênea nas classes grande e pequena.

Palavras-chave: qualidade da madeira, variação radial, plantio de sweetgum.

Abstract

We investigated the effect of diameter class on the wood anatomy and properties of 24-year-old *Liquidambar styraciflua* to determine the potential wood quality in three different diameter classes: large (33cm), medium (26.5cm), and small (22.4cm). We hypothesize that different diameter classes have wood variations with potential distinct qualities. Results showed the highest values of compression parallel to the grain, shear parallel to the grain and modulus of rupture in the small and medium classes. Radial variation showed an increase in vessel diameter, decrease in the frequency of vessels, and increase in the fiber length toward the bark. In contrast to other studies, longer fibers were found, possibly associated with climatic conditions. Density did not vary among the three classes, but it was more homogeneous in the large and medium classes, but not the small class. Stiffness was more homogeneous in the large and small classes.

Keywords: wood quality, radial variation, sweetgum planting.

INTRODUCTION

Liquidambar styraciflua L. (sweetgum), Altingiaceae, naturally grows in many states of the U.S. along the Atlantic coast, as well as Mexico and Central American countries of Guatemala, Belize, El Salvador, Honduras, and Nicaragua (KORMANIK, 1990). According to Luppold and Bumgardner (2004), the wood is used for furniture, composites, pallets, and paper products, and has a more diverse market than softwoods. Almost all lumber is produced in the southeastern United States (WIEMANN, 2010).

In Brazil, the *Pinus* and *Eucalyptus* woods are widely used for purposes such as lumber and furniture, but *Liquidambar* can be a useful and profitable alternative to these woods, as well as contribute to the preservation of native forests. McCarter and Hughes (1984) suggested the potential of *L. styraciflua* for planting in the tropics, and in the 1980s, studies with this species were made in Brazil (GALVÃO et al., 1980).

Based on its adaptability and growth, Shimizu and Spir (2004) showed that *L. styraciflua* has great potential for the Brazilian forest sector, especially in the south and southeast, with

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positive results in experimental plantings. The authors found a higher growth rate and productivity in trees whose seeds originated in Central America compared with those from the U.S. and Mexico. Similar results were reported by Sebbenn et al. (2007), who found better performance of 19-year-old *L. styraciflua* coming from Guatemala in contrast to the United States. A growth comparison of *Pinus caribaea* var. *bahamensis* with the best provenance at the same site indicated higher potential of *L. styraciflua* for silviculture in Paraguaçu Paulista City, São Paulo State, Brazil. Based on studies of wood density, Rezende et al. (2007) concluded that the wood of *L. styraciflua* may be an alternative to replace traditional Brazilian woods for the production of furniture, due to the high value-added on furniture and increasing difficulties of Brazilian noble hardwoods from native forests exploitation.

Mattos et al. (2001), who studied the wood features of *L. styraciflua* in Paraná State (Brazil), reported a lack of studies on the wood features, information which could be very useful in providing guidance for the end use of this wood.

The effect of radial growth rate on wood quality is also essential to choose the correct spacing and management of timber species. Saranpää (2003) reported several studies that evaluated the effect of growth rate on wood density with contradictory results, but usually diffuse-porous hardwoods show little or no relationship between growth rate and wood density, which is one of the best predictors of other wood properties. Thus, depending on the species, the growth rate effects are more or less accentuated, with respect to *L. styraciflua* Jeffries (2008) did not observe any significant effect of growth rate on the wood quality, although the author reported correlations between the properties of wood and stem location.

As highlighted above, many reports have focused on the growth and productivity of *L. styraciflua* in Brazil; however, little information about the quality of wood produced in these plantations can be found. Therefore, our goal was to determine the anatomical features and key properties of *Liquidambar styraciflua* wood in three different diameter classes to evaluate the potential wood quality, thereby filling this gap in our knowledge. We hypothesize that different diameter classes have wood variations that imply distinct qualities.

MATERIALS AND METHODS

The samples were collected at the Mogi Mirim Experimental Station (MMES), São Paulo State, Brazil at 23° 43′ south latitude and the 48° 28′ west longitude, at an altitude above 600 meters. The climate is humid subtropical, i.e., Cwa by Köppen classification, and the soil is sandy and classified as Oxisol, or medium textured sandy loam (TOLEDO FILHO et al., 1989).

Liquidambar styraciflua (3 x 2 m) was planted at the (MMES) in 1984, and the 24-year-old trees were cut in 2008. No management of the planting took place, and the survival rate was 89.5% in 2007 at age 19 (SEBBENN et al., 2007). The selection for the cut was based on a forestry inventory, we choose trees from classes based on the diameter at breast height (DBH) which is the diameter at 1.30 m height: small, medium and large. In each class, four trees were evaluated, totaling 12 trees (Table 1).

A butt log 1.3 m long was removed from the base of each tree, and a central plank was cut. We took a block 7.5 cm long in the upper region of each plank (corresponding to 1.3 m). Anatomical analysis and two physical properties, including basic specific gravity and volumetric shrinkage, were based on samples taken from the blocks. From butt log were cut samples for mechanical testing (Figure 1).

Samples taken from the plank were kept in a room for 2 months with constant conditions of relative humidity and temperature and then the samples for each test were cut in their final dimensions. Five samples per tree for each variable were used from pith to bark: 0 (pith not included), 25, 50, 75, 100% (bark). For each analysis detailed below (anatomy and physical and mechanical tests), considering the radial positions, we studied five samples from each tree, 20 samples in each diameter class, totaling 60 samples (Figure 1).

Blocks of 2 cm^3 were softened in boiling water and glycerin (4:1), and sections 15-25 mm thick were prepared on a sliding microtome. The transverse and longitudinal sections (A) were bleached with 60% sodium hypochlorite and washed in water (JOHANSEN, 1940). Macerations (B) were prepared according to the modified Franklin method (BERLYN; MIKSCHE, 1976), to study the radial variation of length and wall thickness of the fibers and to determine whether these features are

Table 1. Information about 24-year-old *Liquidambar styraciflua* trees planted in Mogi Mirim Experimental Station, São Paulo State, Brazil.
Tabela 1. Informações sobre as árvores de *Liquidambar styraciflua* aos 24 anos, plantadas na Estação Experimental de Mogi Mirim, São Paulo, Brasil.

Diameter class (DBH)	Tree n°	DBH (cm)	Mean DBH (cm)	Height (m)	Mean height (m)
Large	1	31	33	26.4	26
	2	32		25.0	
	3	33		25.8	
	4	36		26.9	
Medium	5	25.5	26.5	26.9	27.1
	6	26.5		27.4	
	7	27		27.4	
	8	27		26.9	
Small	9	22	22,4	25.3	25.7
	10	22		23.6	
	11	22		27.2	
	12	23.5		26.6	

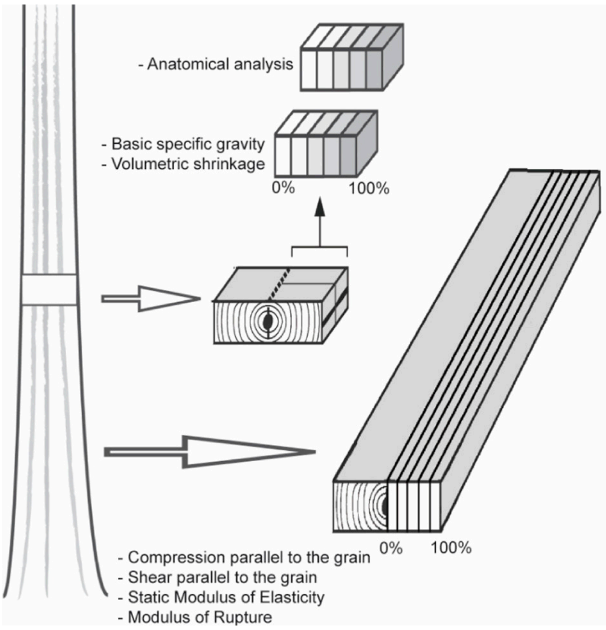

Figure 1. Schematic illustration of wood samples for anatomical analysis and essays of physico-mechanical properties.
Figura 1. Representação esquemática da amostragem para as análises anatômicas e propriedades físico-mecânicas.

influenced by age (number of growth rings) or stem diameter were also remove fragments from each growth ring (we counted 21 rings) from pith to bark. A and B were stained with aqueous safranin and mounted in a solution of water and glycerin (1:1). The terminology and characterization of wood followed the IAWA list (IAWA COMMITTEE, 1989). Because of the extremely long rays, this feature was difficult to establish with our equipment, and, therefore, it was not determined.

All anatomical measures were performed on a microscope (Olympus CX 31) equipped with a camera (Olympus Evolt E330) and a computer with image analyzer software (Image-Pro 6.3).

From each plank, five 2 x 2 x 50 cm samples (pith-bark) were taken to measure specific gravity, compression parallel to the grain, shear parallel to the grain, volumetric shrinkage, static modulus of elastic (MOE) and modulus of rupture (MOR). The methodologies for each assay are described below.

Basic specific gravity (Gb) was determined according to Glass and Zelinka (2010). Samples of 2 x 2 x 3 cm were saturated by treatment with a vacuum system for 72 h to obtain green volume of wood. In sequence, the samples were dried in a laboratory kiln to determine the oven-dried mass at 102 ± 3 °C. Volumetric shrinkage was determined according to ABNT (1997) and was obtained from the same samples as those used to measure basic density. The samples were saturated in water, measured with a caliper, and oven-dried at 102 ± 3 °C. The dry volume of each sample was then determined. The difference in percentage between the two measurements is the volumetric shrinkage.

Samples of 2 x 2 x 3 cm measured with a caliper (accuracy: 0.01-0.05 mm) to determine the area of each sample (12% moisture content) were tested in a Universal Assay Machine (ABNT, 1997). Compression test parallel to grain was performed. We used the same application rate of strain (loading rate of the NBR 7190), of 10 MPa/min. Samples of 2 x 2 x 3 cm with 5 cm² shear area were assayed; at one end was a characteristic cut of the shear samples (ABNT, 1997). The samples had previously been measured with a caliper to determine the areas of each sample (12% moisture content). The load application velocity was 2.5 MPa/min.

To the bending essay samples of 2 x 2 x 35 cm were dried at room temperature up to 12% moisture content. Bending tests were conducted on a universal machine with velocity assay load of 10 MPa/min. We used a combination of the standard MB 26 and ASTM D143 – 94 (ASTM, 1994), i.e., with dimensions (bxh) 2 x 2 cm cross section and 30 cm span (L) resulting in a L / h ratio of 15.

We initially performed descriptive statistical analysis to determine the mean, minimum and maximum values, considering all radial positions. We performed the Normality Test to observe the distribution of data. For pith-bark characterization, the radial positions were considered separately, and based on the normal data distribution; a parametric analysis of variance (One Way Analysis of Variance) was performed, both for diameter classes and radial variation. When a significant difference was observed, we employed the Tukey test to identify pairs of significantly different means.

RESULTS

Averages of three classes

In each class, we placed together all radial values (0, 25, 50, 75 and 100%) in each class to derive the final mean values. Among the anatomical features, variations occurred in fiber length, vessel frequency, ray width and frequency (Table 2). Fibers were longer in the medium and small classes; vessel frequency was higher in the small and large classes, and the width and frequency of rays were higher in the medium and large classes.

Variations in properties were observed in compression parallel to the grain (CPG), shear parallel to the grain (SPG) and modulus of rupture (MOR). CPG, MOR and SPG were higher in the small and medium classes (Table 3).

Radial variation in each class

Toward the bark, we note the anatomical variations in the three diameter classes. In general, fiber length, fiber wall thickness (Fig. 2a,d), vessel element length and vessel diameter (Fig. 4a,b) were higher near the bark compared to pith. Larger diameter vessels near the bark when compared with the pith are shown in figure 5. Radial variation was not evident to fiber diameter (Fig. 2b). Fiber lumen diameter (Fig. 2c) and vessel and ray frequencies (Fig. 4c,d) were lower near the bark than near the pith. Ray width did not vary radially. Fiber length showed a tendency to increase from pith to the bark in the three diameter classes. Fiber wall thickness showed a tendency to decrease from growth ring 13 in the small class, and tendency to increase in other two classes from pith to the bark (Fig. 3a,b). In general, basic specific gravity (BSG) showed practically no radial variation (Fig. 6a), while values of SPG and MOE were higher in the bark compared to pith (Fig. 6b,c).

Table 2. Averages of anatomical features in the three diameter classes in 24-year-old *Liquidambar styraciflua* planted in Mogi Mirim Experimental Station, São Paulo State, Brazil.
Tabela 2. Médias das características anatômicas nas três classes de diâmetro de *Liquidambar styraciflua* aos 24 anos de idade, plantadas na Estação Experimental de Mogi Mirim, São Paulo, Brasil.

Diameter class (DBH)	FL (µm)	FD (µm)	FLD (µm)	FWT (µm)	VEL (µm)	VD (µm)	VF (n.mm^{-2})	RW (µm)	RF (nº.mm^{-1})
Large	1983b	30a	15a	7.2a	1355a	64a	70ab	36ab	8.0ab
Medium	2213a	29a	14a	7.5a	1450a	64a	68b	39a	8.4a
Small	2043ab	29a	15a	7.2a	1383a	66a	76a	35b	7.5b

Means followed by different letters in the same column differ at P < 0.05 by Tukey test. FL = Fiber length, FD = Fiber diameter, FLD = Fiber lumen diameter, FWT = Fiber wall thickness, VEL = Vessel element length, VD = Vessel diameter, VF = Vessel frequency, RW = Ray width, RF = Ray frequency.

Médias seguidas de letras diferentes na mesma coluna diferem em P < 0.05 pelo teste de Tukey. FL = Comprimento da fibra, FD = diâmetro da fibra, FLD = diâmetro do lume da fibra, FWT = espessura da parede da fibra, VEL = comprimento do elemento de vaso, VD = diâmetro do vaso, VF = frequência do vaso, RW = largura do raio, RF = frequência do raio.

Table 3. Average of physical and mechanical properties in the three diameter classes in 24-year-old *Liquidambar styraciflua* planted in Mogi Mirim Experimental Station, São Paulo State, Brazil.
Tabela 3. Médias das propriedades físicas e mecânicas nas três classes de diâmetro de *Liquidambar styraciflua* aos 24 anos de idade, plantadas na Estação Experimental de Mogi Mirim, São Paulo, Brasil.

Diameter class (DBH)	BSG (g cm^{-3})	CPG (MPa)	SPG (MPa)	VS (%)	MOE (MPa)	MOR (MPa)
Large	0.48a	36.1b	6.1b	15.4a	7779.3a	62.4b
Medium	0.49a	39.0a	7.5a	16.4a	8785.8a	76.7a
Small	0.48a	37.6ab	7.0a	15.7a	7847.4a	72.1ab

Means followed by different letters in the same column differ at P < 0.05 by Tukey test. BSG = Basic specific gravity, CPG = Compression parallel to the grain, SPG = Shear parallel to the grain, VS = Volumetric shrinkage, MOE = Static Modulus of Elasticity, MOR = Modulus of rupture.

Médias seguidas de letras diferentes na mesma coluna diferem em P < 0.05 pelo teste de Tukey. BSG = Densidade básica, CPG = Compressão paralela à grã, SPG = Cisalhamento paralelo à grã, VS = Retração volumétrica, MOE = Módulo de elasticidade, MOR = Módulo de ruptura.

Anatomy x properties correlation

The MOE and CPG were properties that most correlated with the anatomical features (Tables 4-6). We emphasize that the correlation between MOE and FL and VD was positive in all three classes, while VF correlated negatively with SPG and MOR. Note that all correlations between VF and ray features with wood properties were negative. Similarly, VS showed negative correlations with all four anatomical features.

DISCUSSION

Averages of three classes

The fibers of the large class were shorter than those of the medium class, which could affect the finishing quality. Specifically, when planning the wood, shorter fibers are torn more easily than longer fibers which would cause uneven surfaces and raised fibers, thereby reducing the quality of the finish (SILVA et al., 2005). We cannot say that the difference between the average fiber

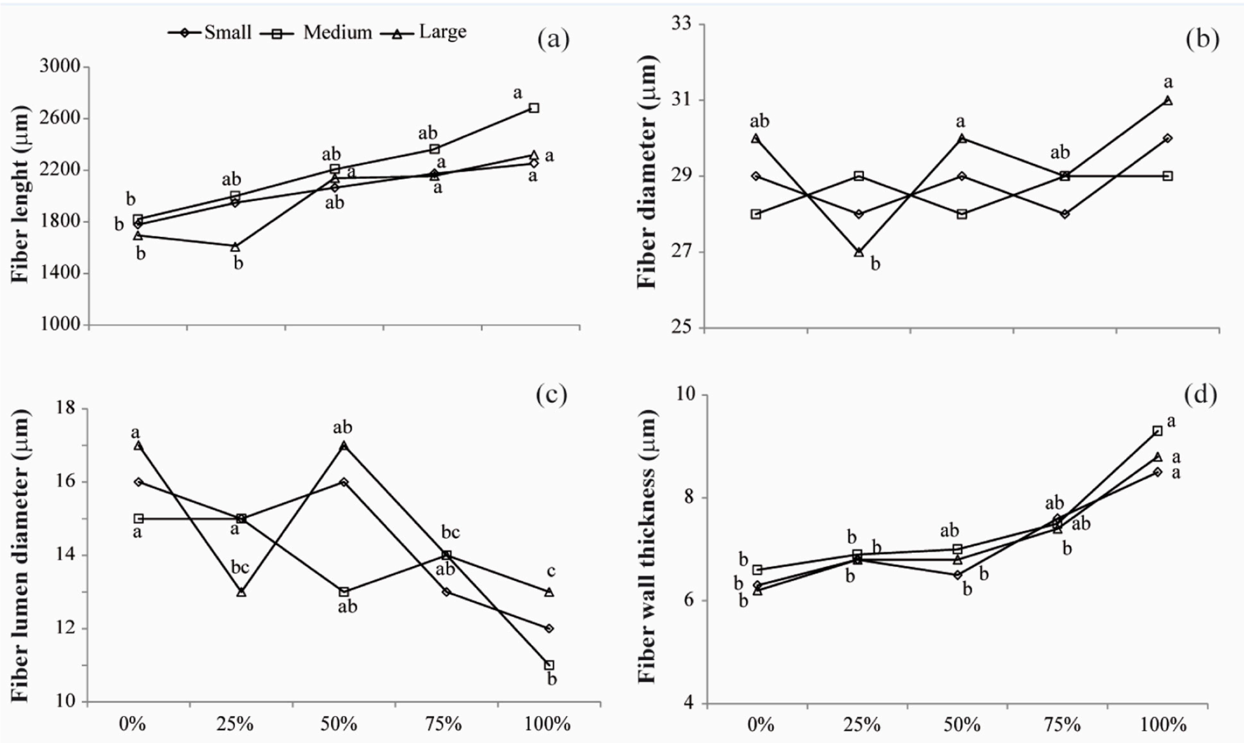

Figure 2. Radial variation in fiber dimensions in the three diameter classes in 24-year-old *Liquidambar styraciflua* planted in Mogi Mirim Experimental Station, São Paulo State, Brazil. Distinct letters differ statistically the radial positions in each diameter class at P < 0.05 by Tukey test.

Figura 2. Variação radial das dimensões das fibras nas três classes de diâmetro de *Liquidambar styraciflua* aos 24 anos de idade plantadas na Estação Experimental de Mogi Mirim, São Paulo, Brasil. Letras distintas diferem estatisticamente entre as posições radiais em cada classe de diâmetro em P < 0.05 pelo teste de Tukey.

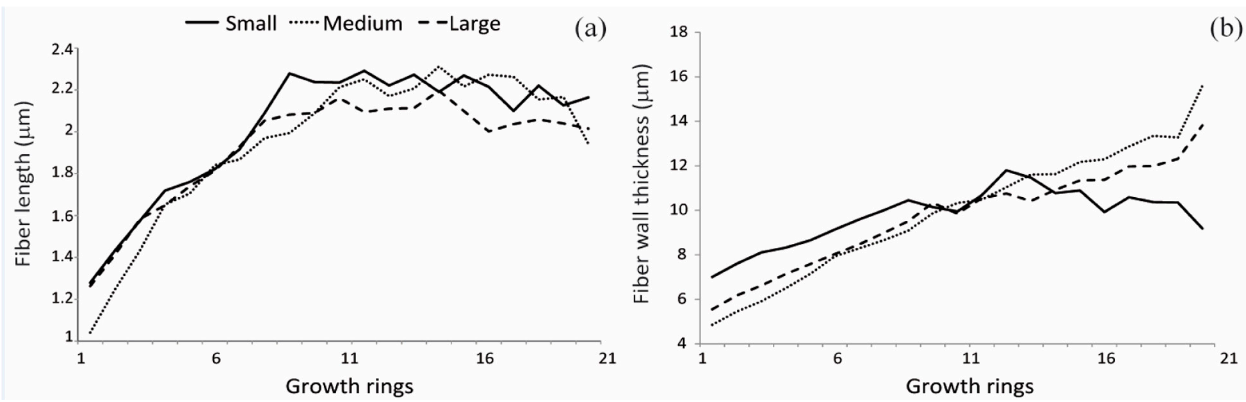

Figure 3. Radial distribution of fiber length and fiber wall thickness along growth rings from small, medium and large diameter classes in 24-year-old *Liquidambar styraciflua* planted in Mogi Mirim Experimental Station, São Paulo State, Brazil.

Figura 3. Distribuição radial do comprimento e espessura da parede das fibras ao longo dos anéis de crescimento das classes: grande, média e pequena de *Liquidambar styraciflua* aos 24 anos de idade plantadas na Estação Experimental de Mogi Mirim, São Paulo, Brasil.

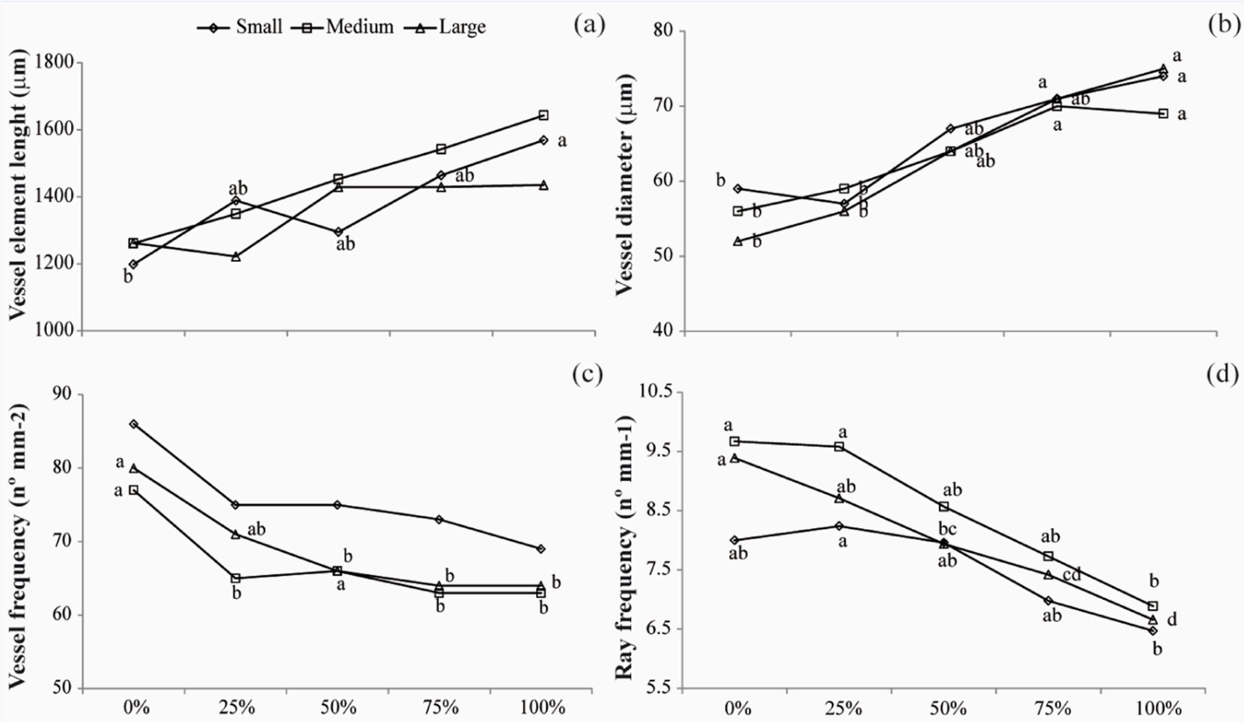

Figure 4. Radial variation in vessels and ray in the three diameter classes in 24-year-old *Liquidambar styraciflua* planted in Mogi Mirim Experimental Station, São Paulo State, Brazil. Distinct letters differ statistically the radial positions in each diameter class at P < 0.05 by Tukey test.

Figura 4. Variação radial dos vasos e raios nas três classes de diâmetro de *Liquidambar styraciflua* aos 24 anos de idade plantadas na Estação Experimental de Mogi Mirim, São Paulo, Brasil. Letras distintas diferem estatisticamente entre as posições radiais em cada classe de diâmetro em P < 0.05 pelo teste de Tukey.

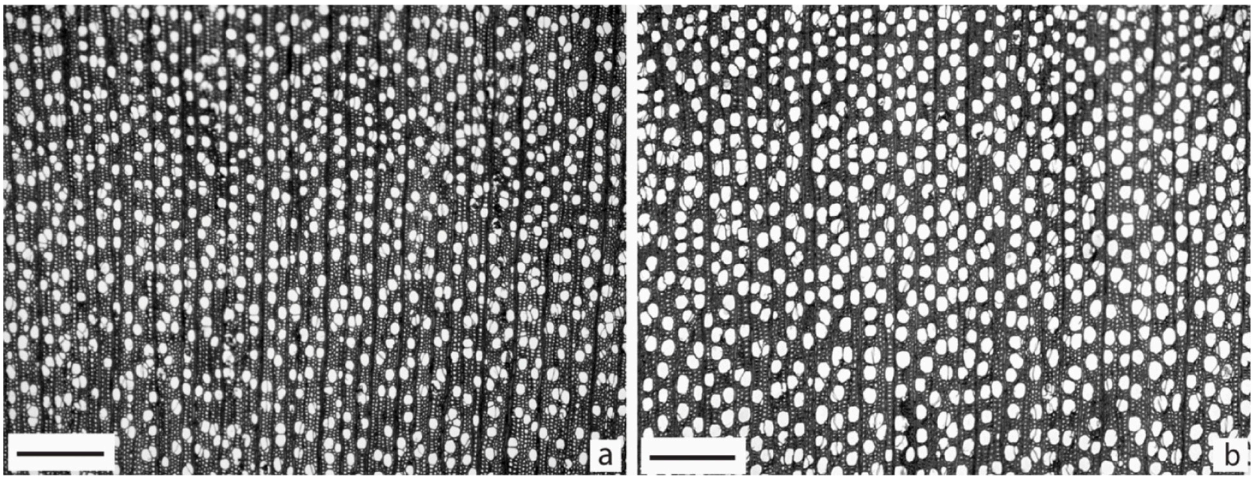

Figure 5. Transverse sections of *Liquidambar styraciflua*. a. Pith region. b. Bark region. Note increase of vessel diameter. Scale bar = 100 µm.

Figura 5. Secções transversais de *Liquidambar styraciflua*. a. Região da medula. b. Região da casca. Notar aumento no diâmetro dos vasos. Barra de escala = 100 µm.

Table 4. Pearson correlation coefficients between anatomical features and physical and mechanical properties in the large diameter class. Upper and lower values indicate correlation coefficients and P values, respectively. For abbreviations, see Tables 2 and 3.

Tabela 4. Coeficientes de correlação de Pearson entre características anatômicas e propriedades físico-mecânicas na classe de diâmetro grande. Os valores acima e abaixo indicam os coeficientes de correlação e os P valores, respectivamente. Para abreviações, ver Tabelas 2 e 3.

	Anatomical Features			
Properties	**FWT**	**VD**	**VF**	**RF**
CPG	0.65 0.0016	0.54 0.0122	ns	-0.56 0.0091
SPG	ns	ns	-0.45 0.0439	ns
MOE	0.65 0.0019	0.69 0.0007	ns	-0.64 0.0020
MOR	ns	ns	-0.45 0.0432	ns

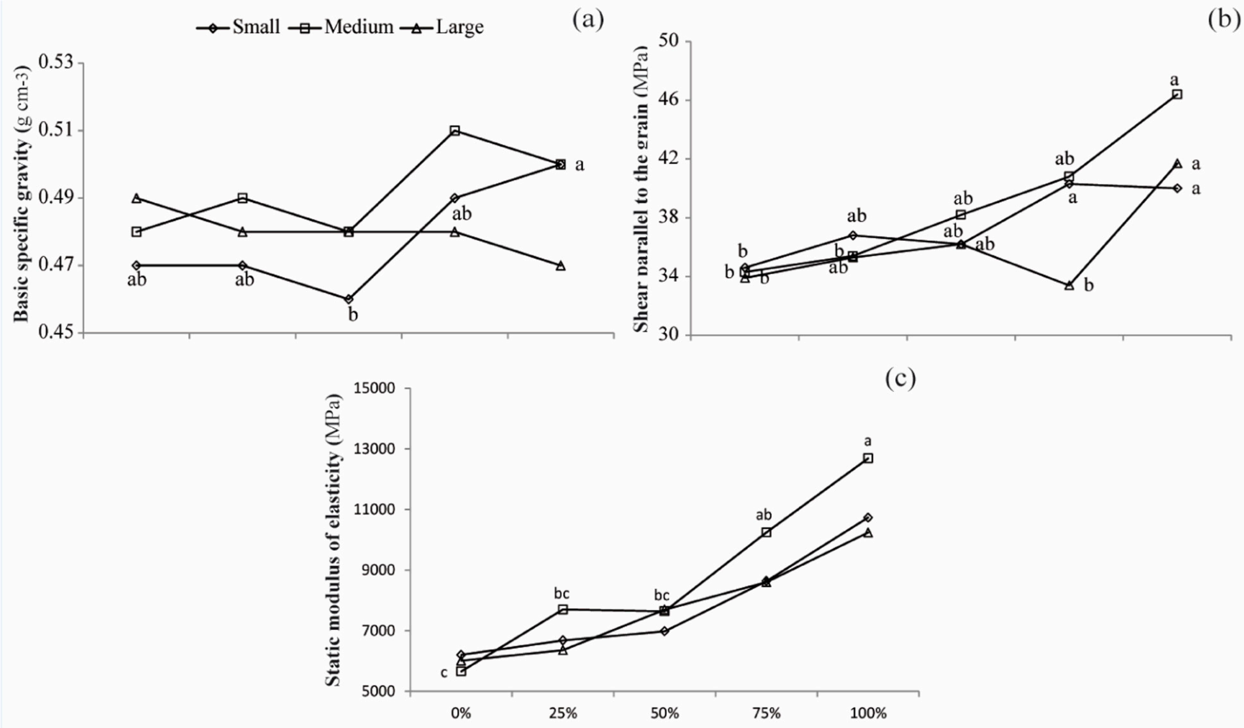

Figure 6. Radial variation in the basic density, compression parallel to the grain and static modulus of elasticity in the three diameter classes in 24-year-old *Liquidambar styraciflua* planted in Mogi Mirim Experimental Station, São Paulo State, Brazil. Distinct letters differ statistically the radial positions in each diameter class at P < 0.05 by Tukey test.

Figura 6. Variação radial da densidade básica, compressão paralela à grã e módulo de elasticidade estático nas três classes de diâmetro de *Liquidambar styraciflua* aos 24 anos de idade plantadas na Estação Experimental de Mogi Mirim, São Paulo, Brasil. Letras distintas diferem estatisticamente entre as posições radiais em cada classe de diâmetro em P < 0.05 pelo teste de Tukey.

Table 5. Pearson correlation coefficients between anatomical features and physical and mechanical properties in the medium diameter class, upper and lower values indicate correlation coefficients and P values, respectively. For abbreviations, see Tables 2 and 3.

Tabela 5. Coeficientes de correlação de Pearson entre características anatômicas e propriedades físico-mecânicas na classe de diâmetro média. Os valores acima e abaixo indicam os coeficientes de correlação e os P valores, respectivamente. Para abreviações, ver Tabelas 2 e 3.

	Anatomical Features					
Properties	**FLD**	**FWT**	**VD**	**VF**	**RW**	**RF**
CPG	-0.60 0.0049	0.49 0.0266	0.51 0.0208	-0.52 0.0176	ns	ns
SPG	ns	ns	ns	-0.48 0.0304	ns	ns
VS	ns	ns	-0.46 0.0365	ns	-0.48 0.0292	ns
MOE	-0.68 0.0009	0.73 0.0002	0.55 0.0104	-0.55 0.0115	ns	-0.49 0.0272
MOR	ns	ns	ns	-0.48 0.0304	ns	ns

Table 6. Pearson correlation coefficients between anatomical features and physical and mechanical properties in the small diameter class, upper and lower values indicate correlation coefficients and P values, respectively. For abbreviations, see Tables 2 and 3.

Tabela 6. Coeficientes de correlação de Pearson entre características anatômicas e propriedades físico-mecânicas na classe de diâmetro pequena. Os valores acima e abaixo indicam os coeficientes de correlação e os P valores, respectivamente. Para abreviações, ver Tabelas 2 e 3.

	Anatomical Features		
Properties	**FLD**	**FWT**	**VD**
BSG	-0.59 0.0061	0.72 0.0003	0.53 0.0156
CPG	-0.74 0.0002	0.84 <.0001	0.50 0.0231
MOE	ns	0.69 0.0006	0.63 0.0027

length (0.23 mm) between two classes (large and medium, see table 2) is sufficient to provide the highest quality of finishing to the medium class.

Rays also influence the quality of the finish by having weaker cells than fibers, and their orientation rarely coincides with the worked surface, making it difficult to obtain a smooth surface (HOADLEY, 2000). When analyzing only the ray features, the evidence indicated that the wood of large and small classes would provide a better surface, since these classes have less bulky rays. However, the small class has a larger vessel frequency than the medium class, a feature that also influences wood surface quality because small frequency decreases vessel lines in longitudinal surfaces and can provide a finer texture. Moura et al. (2010) found a positive correlation between vessel dimensions and frequency and wood roughness. Moreover, the risks of rupture, bending and cell detachment were higher in regions around vessels. In another study of the same samples as used in this study, Lima et al. (2013) observed longer cracks in the large class when compared to the small class. In part, this finding results from ray width and frequency in the large class, which showed intermediate values between the medium class (higher value) and small class (lower value).

Compression parallel to the grain, shear parallel to the grain and modulus of rupture did not differ between small and medium classes and showed higher values for than the large class, suggesting that the first two classes must be chosen for the products that require stronger wood. We highlight a high flexibility of *L. styraciflua*, according to this characteristic, the species may be appropriate for making pieces that require marked bends without breaking. Kretschmann (2010) presented information on *L. styraciflua* properties (CPG, SPG, MOE and MOR) at 12% humidity, but all these values were lower in our study, possibly from age, growing conditions and tree growth, information not mentioned in Kretschmann's study.

The lack of variation in basic specific gravity (average value) among diameter classes indicates that the difference in growth was not enough to result in variation in this property, despite the anatomical radial variations that influence wood properties variations, in the present paper we observed radial variation in the basic specific gravity only in small class, as will be discussed below.

Jeffries (2008), in a study of nine-year-old *L. styraciflua* at different heights, found that trees that grew in dominant canopy positions were stronger in compression parallel to grain and denser than other trees. In our study on twenty four-year-old *L. styraciflua*, despite the small difference in height between the diameter classes, we did not observe marked differences around the position 50% ≈ nine-year-old, and the wood of the three classes was more homogeneous.

According to Mattos et al. (2001), *L. styraciflua* wood is suitable for mechanical processing with acceptable values of volumetric shrinkage and anisotropy index. Glass and Zelinka (2010) reported volumetric shrinkage of 15.8%, exactly the same value found in the present study (average of the three classes), despite differences in growth conditions. Therefore, when comparing the climatic characteristics of the United States with those of São Paulo (Brazil), this result may indicate that this property does not present variation regardless of the planting site. This characteristic may be important when considering *L. styraciflua* for fitted wood parts. However, the drying of the wood should be carefully undertaken because it has a high coefficient of shrinkage associated with interlocked grain which can cause excessive deformation (CASSENS, 2012).

Besides the influence of the dimensions and orientations of the cells, the quality of the cutting and finishing of wood depends on grain orientation (HOADLEY, 2000). We did not notice any difference in grain orientation among the three diameter classes. Shimizu (2005) described *L. styraciflua* wood as providing easy workability, although it is subject to warping due to interlocked grain.

Radial variation and potential implications in homogeneity

Radial variation directly influences wood homogeneity, and its study may provide a more rational use of material. Variation in anatomical features and, hence, in properties, is common during the increase in trunk diameter. However, while we noticed that some anatomical features/properties did not vary radially in any tree class studied, we discuss below, in terms of homogeneity, those that did differ among the classes.

Vessel element length (one cell) and vessel length (several vessel elements together vertically) are more related to the water conductivity (CARLQUIST, 2001) than wood properties. Therefore, the lack of variation in vessel element length should not impact the wood properties, and in this study, we found no such correlation, either positive or negative. However, we did observe an increase in vessel diameter in the three classes and a decrease in vessel frequency toward the bark in the large and medium classes, a fairly standard anatomical finding (BAAS et al., 2004). The lack of variation in vessel frequency in small class wood can provide greater uniformity to the material.

Wood cutting of *L. styraciflua* was very easy and we did not observe an evident effect of fiber dimensions on wood cutting quality, despite the interlocked grain, anatomically characterized by fibers angled in different directions, which could hinder the cut, because implies changes in the direction of the band saw, which requires constant alignment.

In our study, we found an increase in the length and thickness of the fibers toward the bark, a common radial pattern in many species (LACHENBRUCH et al., 2011). However, we observed differences in fiber dimensions compared with other studies. For example, Mattos et al. (2001) found fibers of 1550 μm length at 16 years old, lower dimensions than those observed in our study, since even our pith samples already had longer fibers (≈ 1800 mm). This result may be associated with climate because the study region indicated in the Mattos study is colder with the frequent occurrence of frosts, compared to the collection sites in the present study. Our results are supported by those of Randel and Winstead (1976), who observed that the fiber length of sweetgum populations in the United States and Central America were inversely proportional to latitude, and those of Jeffries (2008), who reported that sweetgum fibers are longer in regions of high summer rainfall and longer growing seasons.

We observed a decrease in ray frequency towards the bark in the three diameter classes, showing the same pattern independent of *L. styraciflua* growth rate, but this pattern depends on the species, since Bhat et al. (2001) in *Tectona grandis* and Lei et al. (1997) in *Alnus rubra*, reported positive relationships between ray percentage with growth rate.

Lachenbruch et al. (2011) discussed extensively about the transition from corewood (near the pith) to outerwood (exterior to the core) and showed that this transition may occurs in response to ring number from the pith (cambial age) or in response to stem diameter. Our results of *L. styraciflua* fiber length suggest that transition between young wood to mature wood occurs in response to ring number and not stem diameter, although fiber wall thickness decreased from thirteenth growth ring to the bark in the small class. The reason for the transition from corewood to outerwood (age or stem diameter) varies according to the species, Honjo et al (2005) and Makino et al. (2012) reported that xylem maturation in *Acacia mangium* depends on diameter growth. Kojima et al. (2009) reported that xylem maturation in *Acacia* spp. and *Paraserianthes* spp. depends on diameter growth, and in *Eucalyptus* spp., xylem maturation is controlled by cambium age. Depending on the tree species concerned, these results will be helpful in the development of plantation management programs Kojima et al. (2009).

The lack of radial variation in basic specific gravity in the medium and large classes indicates more homogeneous woods regarding basic specific gravity, which is a key physical property, and may indicate the quality of the mechanical properties of wood. We suggest that planting trees with narrower trunks should be avoided when the aim is to obtain more homogeneous wood for this property.

According to Shimizu (2005), the *L. styraciflua* wood produced in the first ten years has low density, but after that age, density and workability quality increase. Rezende et al. (2007) compared *Pinus tecunumannii* and *L. styraciflua* on plantations in the State of São Paulo (Brazil) and observed lower radial variation in the density of sweetgum, suggesting that the species is less influenced by seasonal variation. According to Kormanik (1990), *L. styraciflua* is a species more adaptable to different climatic and soil conditions. Since we did not observe radial variation in density in the large and medium classes, our results are confirmed by those of Rezende et al. (2007). Although, we observed radial variation of the specific gravity in the small class between the samples near the bark and 50% position, apparently this variation seems to have a little impact on wood quality. Corroborating studies of Saranpää (2003) who mentioned that usually diffuse-porous hardwoods show little or no relationship between growth rate and wood density, and Fan et al. (2012) did not find significant correlation between wood density and diameter growth rate in 40 Asian tropical tree species.

Wood stiffness, as measured by MOE, showed no variation in the small and large classes, suggesting more uniform woods. According to Zhang (1995) mechanical properties of diffuse porous hardwoods are less influenced by growth rate than other properties.

Anatomy x properties correlation and its role in wood quality

While some correlations between anatomy and wood properties are easy to explain, others require further study to be fully understood.

It is expected that fiber properties, by the high proportion of these cells in wood, will have considerable influence. The negative correlation between FLD and BSG is explained by the empty spaces caused by fiber lumen. Consequently, more lumen provides less mass, resulting in lower density (BUTTERFIELD, 2003; MARTÍNEZ-CABRERA et al., 2009). The negative correlation between FLD and CPG observed in medium and large classes may be understood as follows. With more lumen and less mass to resist compression, the tissue is compressed more easily at lower loads. The negative correlation between FLD and MOE can be explained again by the greater amount of space which reduces rigidity. Thus, the higher volume of fiber lumen combined with the higher volume of parenchyma cells may compromise the mechanical stability of wood (MARTÍNEZ-CABRERA et al. 2009).

The positive correlation between FWT and BSG, CPG and MOE, respectively, indicates that thicker walls increase the mass and consequently the density, implying a stiffer and more resistant wood in compression (BUTTERFIELD, 2003). A negative correlation between VD and BSG was expected since higher VD means more empty space; moreover, the influence of VD on BSG should have been minimized by the positive correlation between FWT and BSG. However, a positive correlation between VD and BSG was observed, and the same reasoning, mentioned in the above phrase, explains the positive correlations among VD and CPG and MOE.

The negative correlation between VF and CPG, SPG, MOE and MOR, respectively, results from the greater amount of empty space, allowing lower resistance to these properties. However, the correlations of diameter and vessel frequency with these properties should also be related to radial variation because, generally, higher values of properties are seen close to the bark in mature wood. Thus, the correlation between diameter and vessel frequency in the radial direction should be considered negative (BAAS et al. 2004).

To explain the negative correlations between 1) RW and VS and 2) RF and MOE and CPG, respectively, we understand that the rays provide locking with respect to longitudinally oriented cells, which helps to prevent the growth layers from sliding together in the living tree, as manifested in the propagation of cracks after the tree is cut (MATTHECK; KUBLER 1995, REITERER et al. 2002). Wider rays can decrease wood shrinkage, despite the apparently higher fragility of rays constituted by cell walls that are thinner than the fibers and vessels. However, the bond between these cells may allow a higher determinant opposite the dimensional change of the tissue. In terms of mechanical stresses, higher RF provides less rigid and more flexible timber.

CONCLUSIONS

We confirmed our hypothesis that different diameter classes have wood variations, and these results may potentially imply in variations on wood quality.

Averages of three classes

Woods of the large and small classes can potentially provide better finish than those of the medium class by the presence of longer fibers and less bulky rays. Considering only the large and small classes, the former has lower vessel frequency than small class which can potentially result in better finish. The highest values of CPG, SPG and MOR were noted in the small and medium classes. Density did not vary among the three classes.

Radial variation and potential implications in homogeneity

The variation of anatomical features commonly followed the pattern observed in other studies, e.g., an increase in diameter, decrease in the frequency of vessels, and increase in fiber length toward the bark. We note, however, longer fibers than the values reported in other studies, a result possibly related to climatic conditions. For density, the large and medium classes are more homogeneous than the small class, since they do not vary radially. Stiffness was homogeneous in the large and small classes.

Anatomy x properties correlation and its role in wood quality

Correlations between anatomical characteristics and properties showed how variation in different anatomical features distinctly affects the properties of wood among the three diameter classes.

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